ARMY RESEARCH LABORATORY

Forecast Model Uncertainty; MM5 Accuracy Over Utah

by Barbara Sauter

ARL-TR-3170 **March 2004**

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ARL-TR-3170 **March 2004**

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Computational and Information Sciences Directorate (CISD)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	March 2004
2. REPORT TYPE	Final
3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE	Forecast Model Uncertainty; MM5 Accuracy Over Utah
5a. CONTRACT NUMBER	
5b. GRANT NUMBER	
5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)	Barbara Sauter
5d. PROJECT NUMBER	
5e. TASK NUMBER	
5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	U.S. Army Research Laboratory Computational and Information Sciences Directorate Battlefield Environment Division (ATTN: AMSRL-CI-EB) White Sands Missile Range, NM 88002-5501
8. PERFORMING ORGANIZATION REPORT NUMBER	ARL-TR-3170
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	U.S. Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1145
10. SPONSOR/MONITOR'S ACRONYM(S)	ARL
11. SPONSOR/MONITOR'S REPORT NUMBER(S)	ARL-TR-3170
12. DISTRIBUTION/AVAILABILITY STATEMENT	Approved for public release; distribution is unlimited.
13. SUPPLEMENTARY NOTES	

14. ABSTRACT

Researchers are investigating various approaches to determine and portray weather forecast uncertainty. Methods requiring extensive computing power on the battlefield or massive data communications to the end user will not be implemented in the near future. This study investigated weather forecast uncertainty through a compilation of forecast errors in the Penn State/National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5) over 50 winter days in Utah. The percentage of forecasts meeting the Army's stated accuracy requirements for temperature, dew-point temperature, wind speed, and wind direction is highlighted.

15. SUBJECT TERMS

Weather Forecast Uncertainty; Forecast Accuracy; MM5; Utah MesoWest

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Barbara Sauter
U	U	U	SAR	46	**19b. TELEPHONE NUMBER (*Include area code*)** (505) 678-2840

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Preface

In August, 2002, a group of atmospheric science researchers participated in an Army-Scale Meteorology Workshop at White Sands Missile Range, NM. The U.S. Army Research Laboratory Battlefield Environment Division sponsored the workshop to obtain input on where the Army should invest its atmospheric research resources. One of the participants emphasized that the Army should have information relating to forecast uncertainty.

Some Army decision makers receive weather intelligence from an Air Force Staff Weather Officer, who may use meteorological expertise to provide a range of values or probability information relating to the weather forecast parameters of interest. Often, however, users must rely on the single deterministic value provided by a model such as the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model version 5 (MM5). The Integrated Weather Effects Decision Aid (IWEDA) provides automated red/amber/green guidance on weather impacts on specific military systems based solely on the deterministic model values. Commanders may be able to make better tactical decisions if they are provided information on the amount of certainty associated with a particular forecast.

Several organizations are making forecast uncertainty calculations based on running ensembles of forecast models. However, ensembles are not being run in support of battlefield operations. In response to the workshop recommendation, a limited study was performed to associate forecast model uncertainty with forecast accuracy.

The author acknowledges the contributions of Dr. Teizi Henmi, who set up the MM5 model and observation domain over Utah for a previous study. The existing results from that study included many forecasts of basic surface weather parameters. These forecasts were validated against observations to quantify the occurrences of different error amounts. This report documents the forecast errors seen, with the partially addressed goal of relating the forecast errors to model uncertainty in a way useful to Army decision makers.

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Summary

The meteorological community is recognizing the need for incorporating weather forecast uncertainty along with the forecasts provided to users. A consensus has formed that a forecast range or a confidence level associated with a single forecast value can lead users to make better decisions. On the battlefield, weather intelligence and decision aids are frequently automated, based on a single deterministic value produced by a numerical weather forecast model. Researchers are investigating various approaches to determine and portray weather forecast uncertainty. However, some of these approaches are not currently viable for use on the battlefield because of the amount of computing power or data communications required. This study investigated weather forecast uncertainty in a compilation of forecast errors in the Penn State/National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5).

MM5 forecast outputs were compared to observations of basic surface weather parameters at 50-70 Utah MesoWest sites. The forecasts covered 24 hourly forecasts for each of 50 days during the winter of 2002. The frequency of occurrence of the resulting error amounts was tabulated and is presented in this report. Some effort was included to relate changes in error frequencies to readily available information on the battlefield, such as the month, the forecast time, the observed value, the forecast value, and the station elevation.

These relationships either did not appear to be significant, or the limited time and space of the data included do not allow for useful generalizations to be made. The error data presented may be useful in relaying information to MM5 users on the general model accuracy seen for one specific and difficult forecast location. Emphasis is given to the percentage of forecasts meeting the U.S. Army's stated accuracy requirements for temperature, dew-point temperature, wind speed, and wind direction. The results for the percentage of forecasts that were correct for all the times and stations combined were: 25 percent for temperature within 1° C; 24 percent for dew-point temperature within 1° C; 73 percent for wind speed within 2.5 m/s; and 7 percent for wind direction within 5º. The percentages given for correct wind speed and wind direction forecasts may be misleading. Users will often want wind speed forecasts to be more accurate than plus or minus 2.5 m/s. On the other hand, wind direction forecasts will often be acceptable at less stringent limits than plus or minus 5°.

This report presents a simple approach for using historical error amounts to modify the single forecast value generated by the model to a range of values. This can be accomplished by a user specifying the level of confidence desired in a particular instance or by a human forecaster tagging a specific day's model output with an estimate of high, medium, or low confidence.

1. Introduction

Weather forecast users understand that the forecast may be wrong. When decisions must be made using imperfect weather information, it would be helpful to know the amount of uncertainty associated with the predicted weather. The meteorological community is attempting to address this goal through a variety of approaches, including:

- Categorizing forecast confidence levels based on specific situations and experience.
- Providing a probability or range forecast rather than a single deterministic value.
- Running an ensemble of separate model outputs using different models or different initial conditions for a single model.

An expert weather forecaster may be familiar with a particular model's bias and error tendencies, but these trends often pertain only to a particular place and time. Many users do not have any quantitative knowledge about probable forecast model errors.

On the battlefield, the primary weather forecast model used in support of Army operations is the Penn State/National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5) (*1*). This study quantifies the MM5 forecast errors seen in an existing data set generated in a previous nowcasting research effort (*2*). The results cannot be generalized to other times or locations based on this limited analysis, but they do provide a single set of quantified forecast error occurrences.

2. Methodology

2.1 MM5 Model Runs

Each MM5 model run was initialized with 30 hours of Global Forecast System (GFS) model output data (*3*). The initial 6 hours served as spin-up time prior to the 24 hourly forecast validation times. The MM5 was then run in 3 nests on the Army High Performance Computing Resource Center's Cray computer:

- The outer nest contained 55 x 55 grid points at 45 km grid point spacing for a 2430 x 2430 km domain.
- The middle nest consisted of 55 x 55 grid points at 15 km grid point spacing, covering a 810 x 810 km domain.
- The inner nest included 85 x 85 grid points at 5 km grid point spacing, resulting in a 420 x 420 km domain.

Hourly output from the inner nest was saved each day for 01Z through 00Z, equating to 6 p.m. through 5 p.m. the following day, local Utah time.

The area of the inner nest is shown by the green square in figure 1. The red dots indicate locations registered by the Utah MesoWest cooperative as having surface observing stations, but many of the locations do not report the required data on the hour to be used for these evaluations (*4*). The smaller blue rectangles indicate areas with appropriate stations reporting at the beginning of the study.

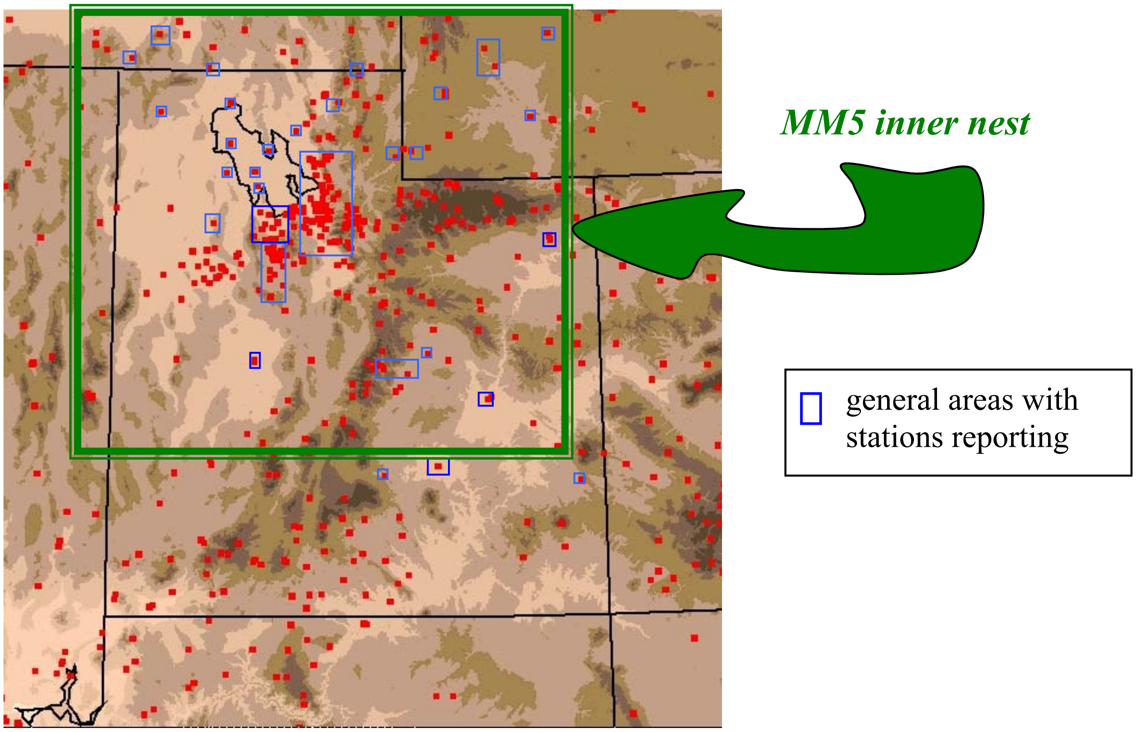

Figure 1. Map of MM5 Inner Nest Model Domain Over Northern Utah.

MM5 forecasts of temperature, dew-point temperature, and u- and v-wind components at the grid points were bilinearly interpolated to the surface station locations. Well over 100 different stations within the MM5 domain reported observations on some of the various days covered. Typically, however, approximately 50-70 stations would be available at a forecast time.

The model forecast runs were performed beginning mid December 2002 through February 2003 for days when the GFS model and the surface observations were available. During this period, a total of 50 days was used, including 8 in December, 18 in January, and 24 in February.

2.2 Forecast Accuracy Analysis

The forecast value of the basic weather parameter provided by the MM5 model was compared to the observed value. Since the ultimate goal is to be able to provide information beneficial to Army decision makers, the error ranges were generally grouped relative to the accuracy requirement stated by Army intelligence experts (*5*). The desired forecast accuracy for both temperature and dew-point temperature is within 1°C. An analysis of relative humidity might be more meaningful to many users than dew-point temperature, but the surface observation stations used in the study reported dew-point temperature and not relative humidity. The Army has specified that wind speed forecasts are needed within an accuracy of 5 kts. An accuracy requirement stated as a percentage of the actual wind speed value would often reflect a more realistic specification than the static value given, but for this analysis the value was simply rounded to 2.5 m/s. Wind direction data were omitted for any observation with wind speed less than 1 m/s to reduce the misleading errors associated with light and variable winds. The Army's wind direction accuracy requirement of 5º is highlighted in this analysis, but in general a more reasonable range of 45° is included.

One of the aims in investigating weather forecast uncertainty is to be able to provide information to decision makers on when the forecast is expected to be more or less accurate. The data set available for this study did not contain information on the actual weather synoptic situations, and no attempt has been made here to associate forecast errors with specific weather scenarios. A list of readily available factors that might be associated with forecast error amounts was devised, to include:

- month
- forecast time
- observed value of parameter
- forecast value of parameter
- station elevation

The following section will provide the forecast errors seen as a function of these variables, although some are covered only briefly.

3. Results

3.1 Forecast Errors Associated with the Month

All of the model runs were performed during a single winter, with 8 days in December, 18 in January, and 24 in February. Basic error statistics are provided separately for each of these three months for temperature and dew-point temperature in table 1 and for wind speed and wind direction in table 2.

Table 1. Forecast Error Statistics by Month for Temperature and Dew-Point Temperature.

		TEMPERATURE (°C)			DEW-POINT (°C)		
		OBS	BIAS	ABS ERR	OBS	BIAS	ABS ERR
DEC	AVG	-3.1	1.0	2.3	-7.5	1.8	2.9
	STDEV	5.4	2.7	1.8	5.0	3.7	3.0
	MAX	11.7	12.6	12.6	3.9	25.4	25.4
	MIN	-23.3	-8.0	0	-35.2	-10.1	0
	COUNT	12000			12000		
JAN	AVG	0.5	2.1	3.0	-5.3	2.4	3.4
	STDEV	4.9	3.3	2.6	5.9	4.4	3.7
	MAX	15.0	29.5	29.5	15.0	50.1	50.1
	MIN	-23.0	-17.0	0	-51.1	-13.2	0
	COUNT	28000			28000		
FEB	AVG	-2.1	1.0	2.5	-7.1	1.1	2.9
	STDEV	6.0	3.2	2.2	6.1	4.1	3.1
	MAX	14.8	42.5	42.5	11.8	65.3	65.3
	MIN	-35.6	-13.6	0	-59.1	-25.4	0
	COUNT	37000			37000		

The left column labeled OBS under each weather parameter contains statistics of the observed data highlighting the large range of values seen, including some erroneous observations. Some bad observations were deleted before running the statistics, but other bad data points were not found until after all the statistical analyses had been calculated. The small number of incorrect reported observations should not have a significant impact on the average error values based on many thousands of validations. The temperature and dew-point temperature forecasts reflect a warm bias in each month, but by differing amounts. The average absolute error values are slightly higher in January than in December or February.

Table 2. Forecast Error Statistics by Month for Wind Speed and Wind Direction.

		WIND SPEED (m/s)			WIND DIRECTION (deg)		
		OBS	BIAS	ABS ERR	OBS	BIAS	ABS ERR
DEC	AVG	3.5	1.0	2.4	183	6	47
	STDEV	3.0	2.9	2.0	91	63	43
	MAX	19.8	11.9	12.3	359	180	180
	MIN	0	-12.3	0	0	-180	0
	COUNT	11000			8000		
JAN	AVG	2.2	0.4	1.7	187	9	61
	STDEV	1.8	2.2	1.5	102	78	49
	MAX	14.5	14.8	14.8	359	180	180
	MIN	0	-10.5	0	0	-180	0
	COUNT	24000			16000		
FEB	AVG	2.7	0.3	1.8	190	10	61
	STDEV	2.4	2.4	1.6	105	77	49
	MAX	23.6	11.4	14.6	359	180	180
	MIN	0	-14.6	0	0	-180	0
	COUNT	32000			24000		

The number of validations for wind direction totals about one-quarter to one-third the number for wind speed. This drop reflects the large percentage of wind observations with speed less than 1 m/s, which were not used in the wind direction statistics. The predominance of light wind speeds contributed to relatively low wind speed errors. The average errors in wind speed and wind direction were virtually identical in the January and February results.

Comparing the forecast accuracies across these three specific months shows that there can be significant differences in the bias or absolute error occurrences. It is impossible to draw any conclusions about long-term error trends associated with a particular month from this limited study. It seems logical that any change in systemic biases might be related to different seasons, but with data from only a single season in a single year, no further investigations relating to monthly differences would be worthwhile.

3.2 Forecast Errors Associated with the Forecast Time

Another factor potentially associated with varying forecast error amounts is the time of day. Since each of the forecast model runs was initialized at 01Z (6 p.m. local time), the following results cannot treat the time of day independently from the lag time of the hourly forecasts from 1-24 hours. In spite of this limitation, the December forecasts were analyzed by time of day by grouping the results in six 4-hour intervals. The average forecast errors were calculated for the following time groups:

- evening (forecast hours 1-4, equating to 6 p.m. - 9 p.m. local time)
- night1 (forecast hours 5-8, 10 p.m. - 1 a.m.)
- night2 (forecast hours 9-12, 2 a.m. - 5 a.m.)
- morning (forecast hours 13-16, 6 a.m. - 9 a.m.)
- midday (forecast hours 17-20, 10 a.m. - 1 p.m.)
- afternoon (forecast hours 21-24, 2 p.m. - 5 p.m.)

Figure 2 shows the results for these time periods for temperature forecasts from the 8 days in December. Points on the graph correspond to the percentage of the forecasts falling within the error category listed on the x-axis. The categories are bands covering 2° C error ranges, extending from an underforecast of 7 to 9º at the left side of the chart to an overforecast of 11 to 13º at the right side. The midday and afternoon forecasts contain slightly less of a warm bias than the other times, but the differences between the different groups of forecast times are not very large. The percentage of the forecasts meeting the Army's stated requirement of temperature forecasts within plus or minus 1° C ranges from 32 percent of the evening forecasts to 27 percent of the afternoon forecasts.

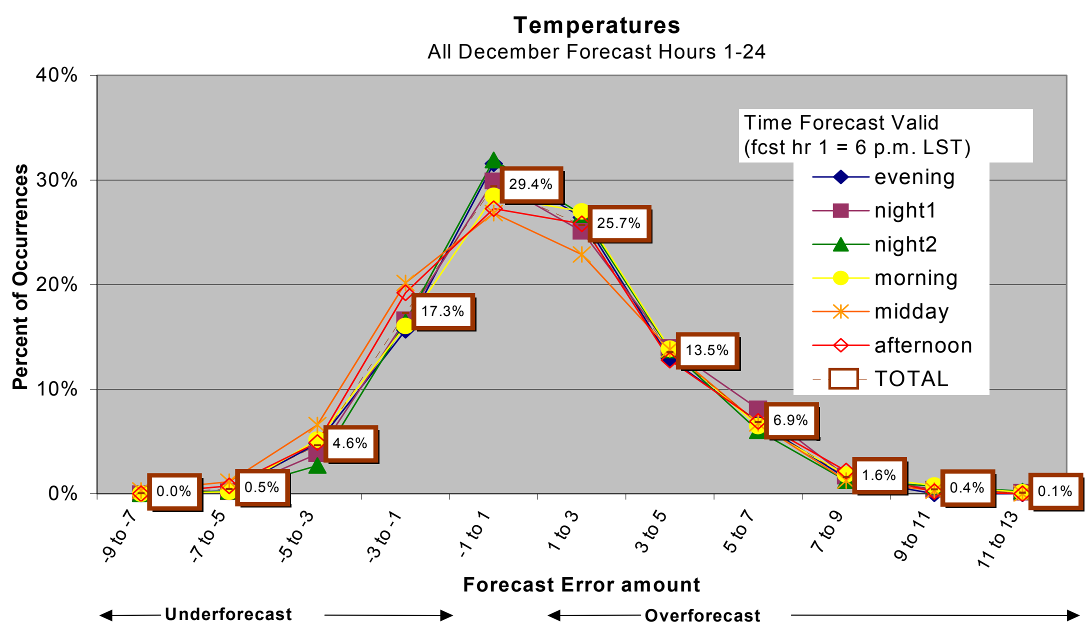

Figure 2. Percentage of Temperature Forecasts with Specified Error Amounts by Time of Day.

A similar chart for wind speed forecast errors is provided in figure 3. The documented Army requirement for wind speed forecasts within plus or minus 2.5 m/s is very broad, particularly in low wind cases. Rather than use consistent 5 m/s error bands providing minimal information, these results show 2.5 m/s error ranges. The percentage of forecasts meeting the Army goal for accuracy can still easily be determined by adding the -2.5 to 0 m/s error occurrences with the 0 to +2.5 m/s errors. The morning forecasts were most likely to contain wind speeds higher than those actually observed. This bias was prevalent throughout all the time periods, based on the generally low wind speeds observed. The percentage of forecasts within the required accuracy varied from 58 percent in the midday forecasts to 68 percent in the evening forecasts.

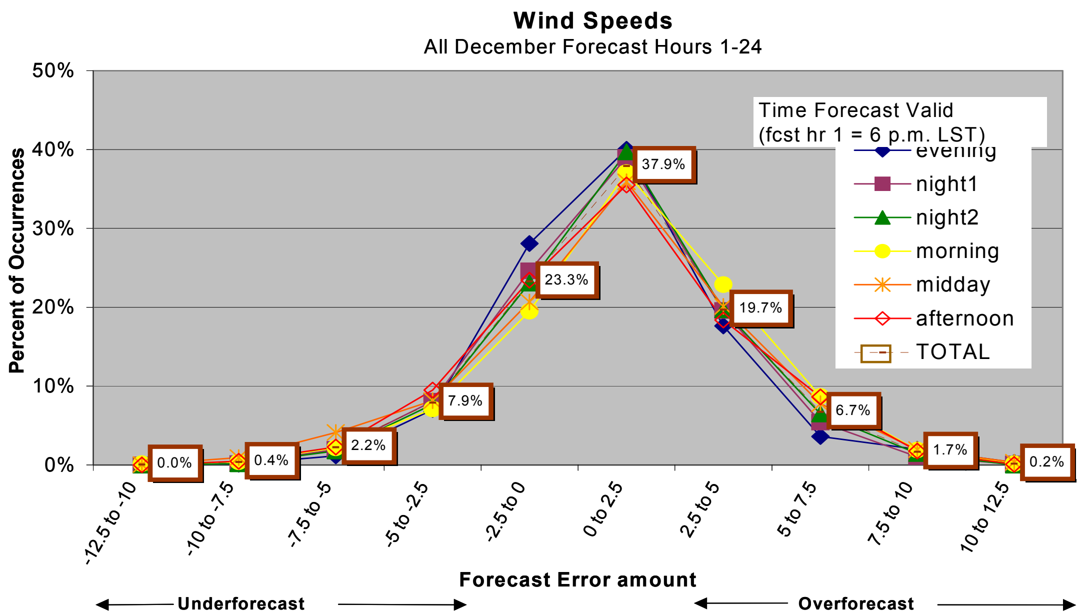

Figure 3. Percentage of Wind Speed Forecasts with Specified Error Amounts by Time of Day.

While the wind speed accuracy requirement of plus or minus 2.5 m/s may be broader than desired, the wind direction forecast goal of plus or minus 5° seems exceedingly stringent. This study incorporates error bands covering 45º, but the errors falling within the -5 to +5° range are totaled separately, in order to specify the percentage of forecasts actually meeting the requirement as it stands. Note that in figure 4, the x-axis values to the left and right of this -5 to 5° point incorporate ranges of 40º each, so summing the errors falling within these three ranges gives the percentage of forecasts accurate within plus or minus 45°. The remaining points include 45° ranges, where of course an error of -180º is identical to an error of +180º. The wind direction error in these cases exhibits a slightly greater bias in the counterclockwise direction in the evening and in the clockwise direction by the afternoon forecast.

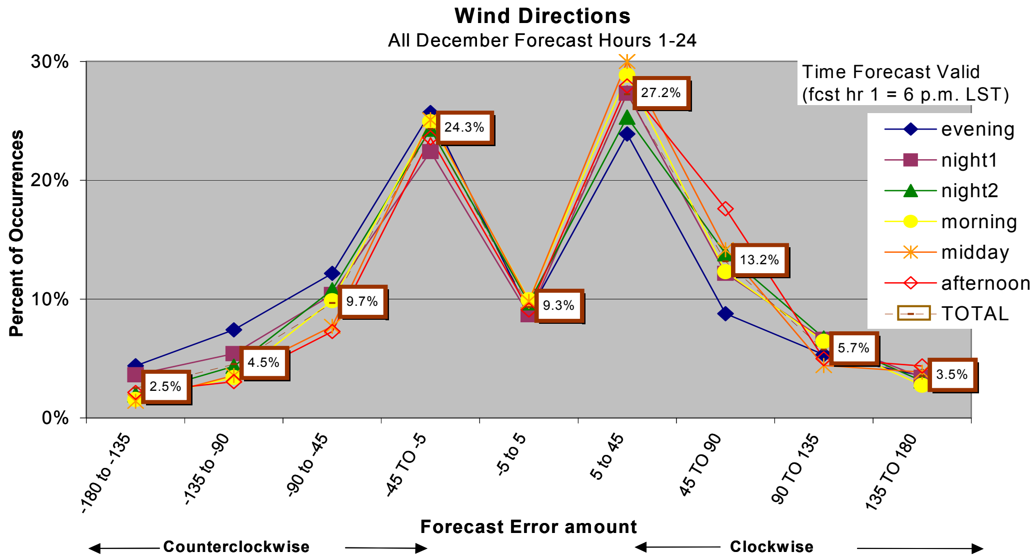

Figure 4. Percentage of Wind Direction Forecasts with Specified Error Amounts by Time of Day.

One aspect to the question, "How good is the forecast model?" is how often it meets the required accuracy. This is certainly too simplistic, especially since the required accuracy depends on the situation rather than being a constant fixed value. However, since this study easily provides the data on how often the required accuracy is satisfied, several charts highlighting this information are included.

Figure 5 summarizes this information by forecast time. The wind speed forecasts show a significant decrease in percent accuracy from the evening forecasts to the morning through afternoon forecasts. The temperature forecasts reflect a small decrease in accuracy by the midday forecasts, although the dew-point temperature forecasts are accurate slightly more often at those times. The wind direction forecasts that fall within 5° of the observed wind direction are depicted by the light green circles, while those within 45º are the dark green circles specified as WD+ in the legend. The 45° criterion is met most frequently during the morning and midday forecast times.

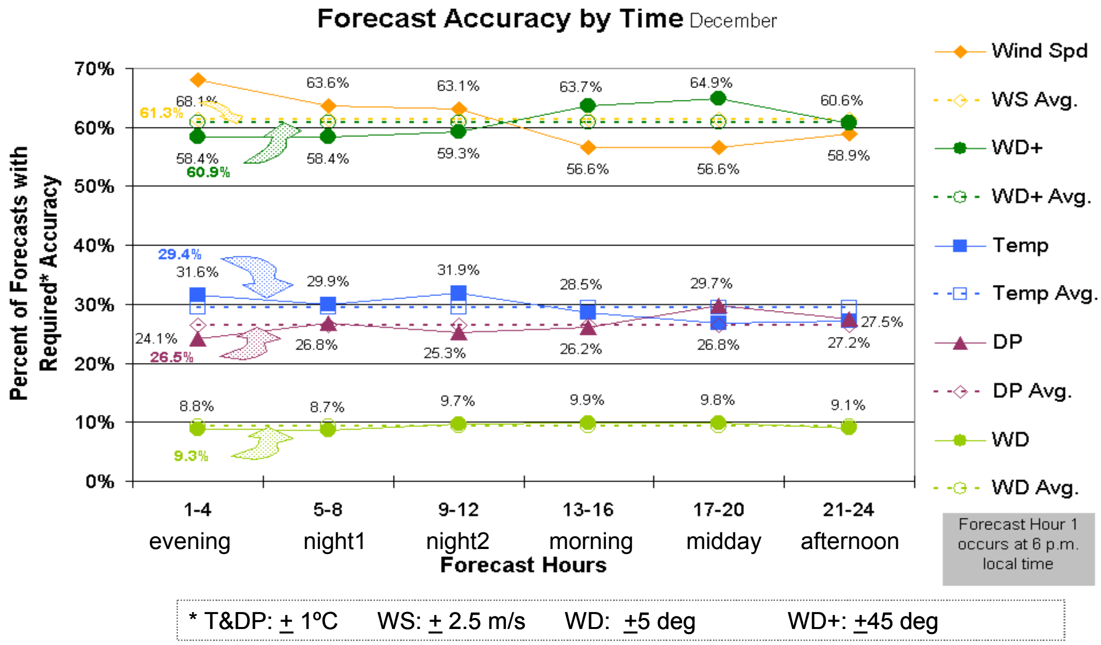

Figure 5. Percentage of Forecasts Satisfying Required Accuracy by Forecast Time.

These results do not show consistent differences in the forecast accuracy between the various times of day. Some of the apparent differences may be attributed to the model start time rather than the relative capability of the model to forecast for different times of the day or night. However, a drop-off in forecast accuracy from the 1-hour to the 24-hour forecasts is not evident to the extent expected. Since the results did not appear promising for providing useful information to decision makers, this analysis by forecast time was not performed for the entire data set after acquiring the January and February data.

3.3 Forecast Errors Associated with the Observed Value of the Parameter

Another analysis considered with the initial December results involved correlating temperature forecast errors with the observed values. Figure 6 reveals these errors as a well-defined function of the actual temperature value reported.

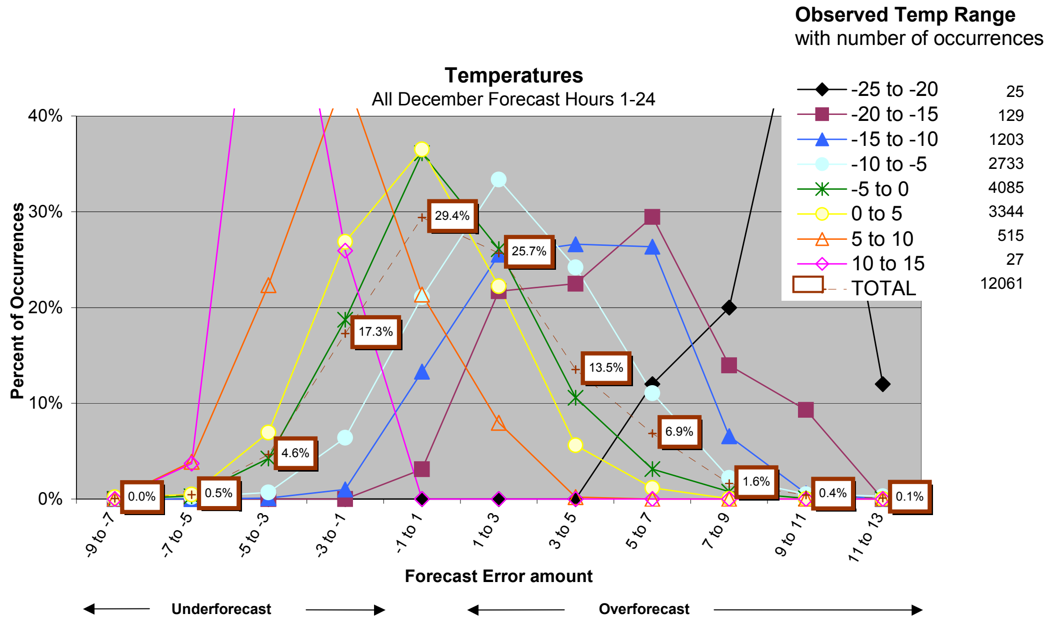

Figure 6. Percentage of Temperature Forecasts with Specified Error Amounts by Observed Temperature Value.

Although the number of cases with observed temperatures in the most extreme categories is small, the trend for the coldest temperatures to be overforecast and for the hottest temperatures to be underforecast is very clear. Figure 7 shows this substantial drop in the percent of forecasts satisfying the plus or minus 1° C accuracy requirement. The percent of forecasts seen as accurate in these December cases was 37 percent when the observed temperature fell between 5 below and 5 above 0° C, but dropped by 10 percent or more in each 5º observed temperature range category moving away from these more moderate values.

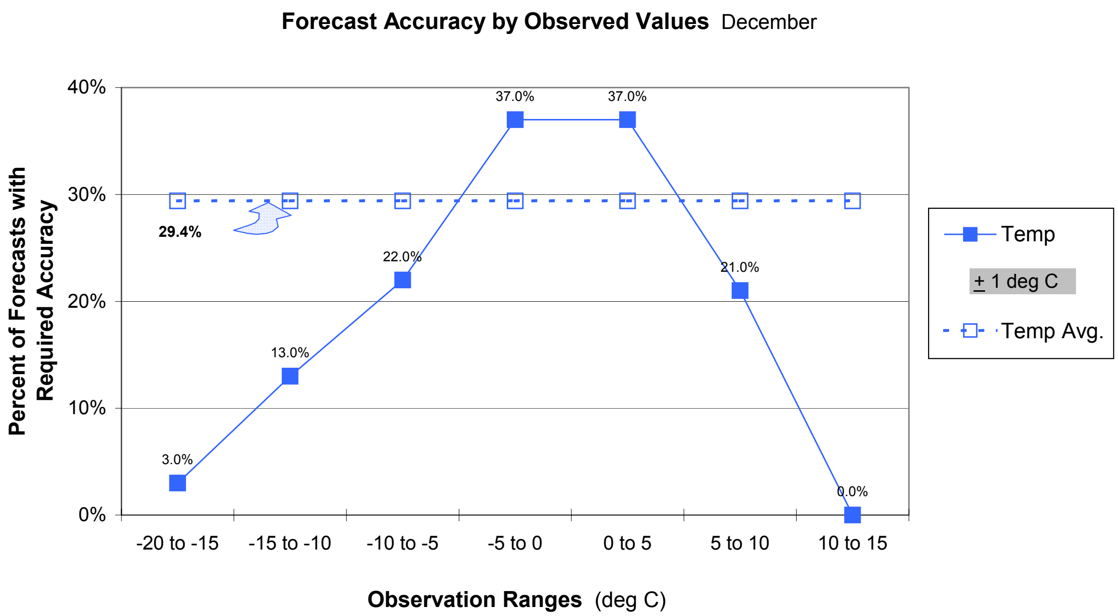

Figure 7. Percentage of Forecasts Satisfying Required Accuracy by Observed Values.

After considering these results, it was decided that the approach of relying on observed values would not be of much benefit to users, since they would not know the observed value ahead of time. It is generally intuitive that extreme cases are more likely to be missed, so no further analyses were performed using this method for the other weather parameters or the January or February data.

3.4 Forecast Errors Associated with the Forecast Value of the Parameter

The association of extreme observations with greater forecast error may be similar to the one expected for extreme forecast values. Human weather forecasters generally believe that "going out on a limb" with a forecast well outside the normal values is usually riskier than a more moderate forecast. Numerical weather forecast models do not temper calculated values that fall far from climatological or persistence-based expectations. The investigations considering forecast values described in this section include the data from all three months used in this study.

As can be seen in figure 8, the bias for predicting too warm temperatures shows up even in the small number of hottest forecasts. Incorporating some sort of bias correction to these forecasts was considered, using the average bias from the preceding month. A quick look at the average bias amounts listed in table 1 indicates that correcting January temperature and dew-point temperature forecasts based on the December bias amounts would have decreased the average error amount. On the other hand, using the January average bias to modify the February forecasts for these parameters would have simply transformed a 1° C warm bias into a 1° C cold bias. Since the data period used in this study was quite limited, no bias correction method was pursued.

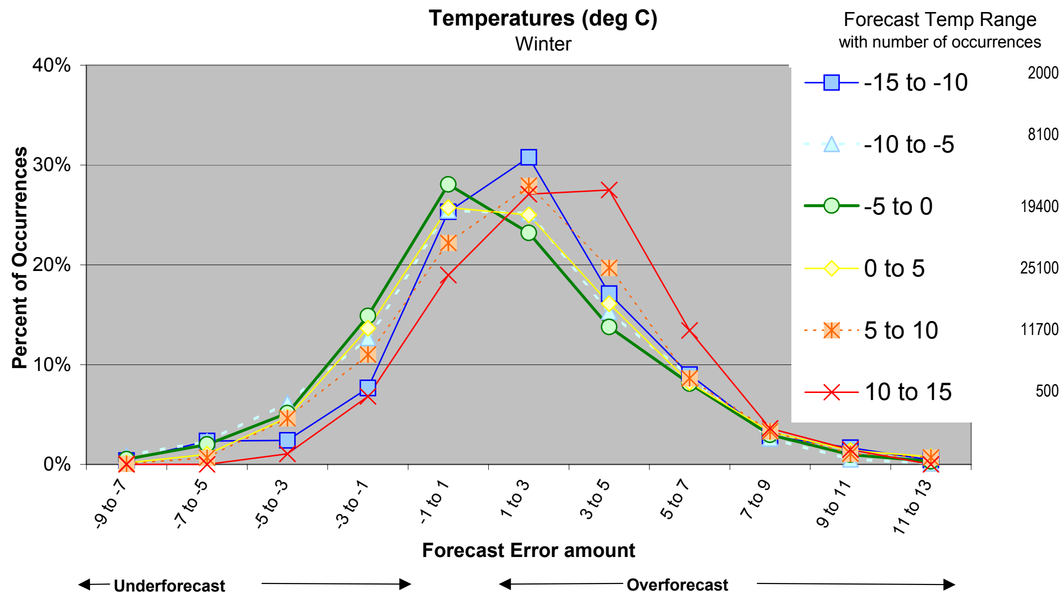

Figure 8. Percentage of Temperature Forecasts with Specified Error Amounts by Forecast Temperature Value.

The great majority of wind speed forecasts were for wind speeds below 2.5 m/s or for wind speeds between 2.5 and 5 m/s. These forecasts were predominantly within the 2.5 m/s accuracy requirement. Figure 9 shows the wind speed errors associated with the wind speed forecast categories. Not surprisingly, the highest wind speed forecasts were much more likely to be too high than too low.

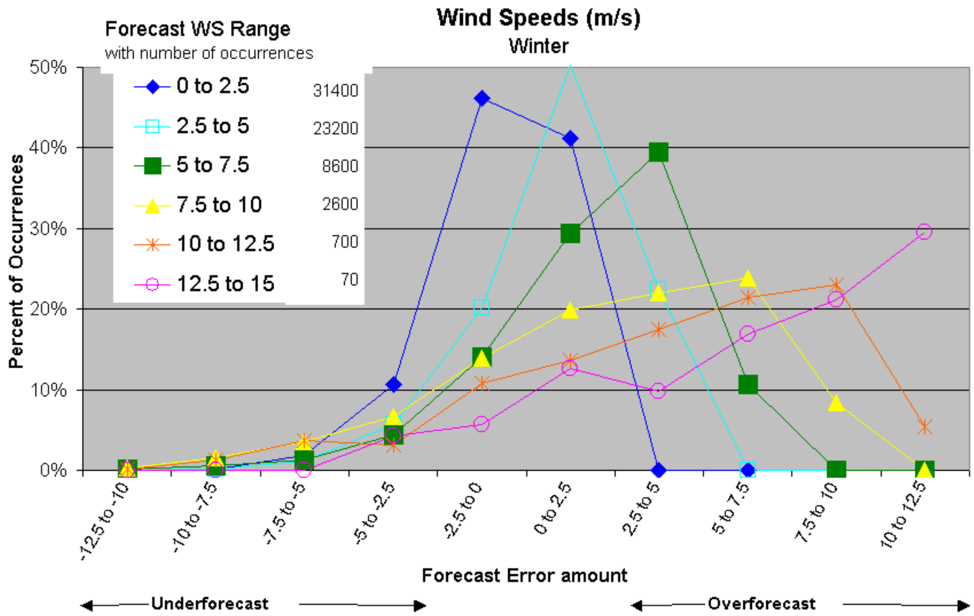

Figure 9. Percentage of Wind Speed Forecasts with Specified Error Amounts by Forecast Wind Speed Value.

Providing useful information relating to general wind direction error tendencies can be more difficult than with other basic weather parameters. Wind direction is frequently listed as one of the most important variables for Army users. However, wind direction rules driven by the numerical forecast are not commonly included in automated decision aids, since the rules typically specify a cross wind or some relative direction rather than a fixed compass direction. Figure 10 consists of forecast errors in wind direction in a similar fashion as previous charts. The eight forecast wind direction range categories are labeled by compass direction name, with each category encompassing 22.5° on either side of the compass point. The average bias amount of wind direction error is a relatively smaller percentage of total error than seen in the other parameters.

Decision makers may not be able to easily use information on wind direction bias. A bar chart is provided in figure 11, incorporating only the December results as an example of an alternate way to view this information. Some people may find the errors stand out somewhat more clearly than in the overlapping line chart, but the chart still requires considerable explanation and study to determine the desired information. In the bar chart, the forecast wind direction categories displayed on the x-axis are equivalent to those used as separate lines in figure 10. The forecast error categories associated with each individual forecast direction are portrayed in a separate color. However, the error categories themselves are not identical, because in the bar chart the errors are counted according to observed compass direction categories as opposed to strictly the number of degrees difference in the forecast and observed wind values. A small error could occasionally result in a validation in the neighboring category. The information contained in the bars in figure 11 is described after the figure.

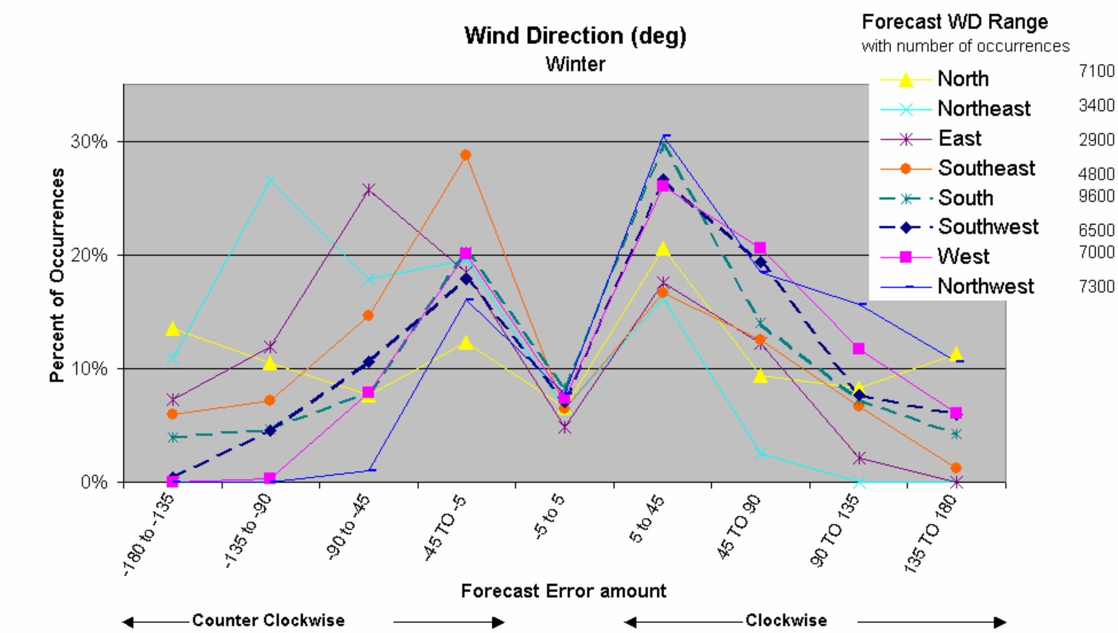

Figure 10. Percentage of Wind Direction Forecasts with Specified Error Amounts by Forecast Wind Direction Value.

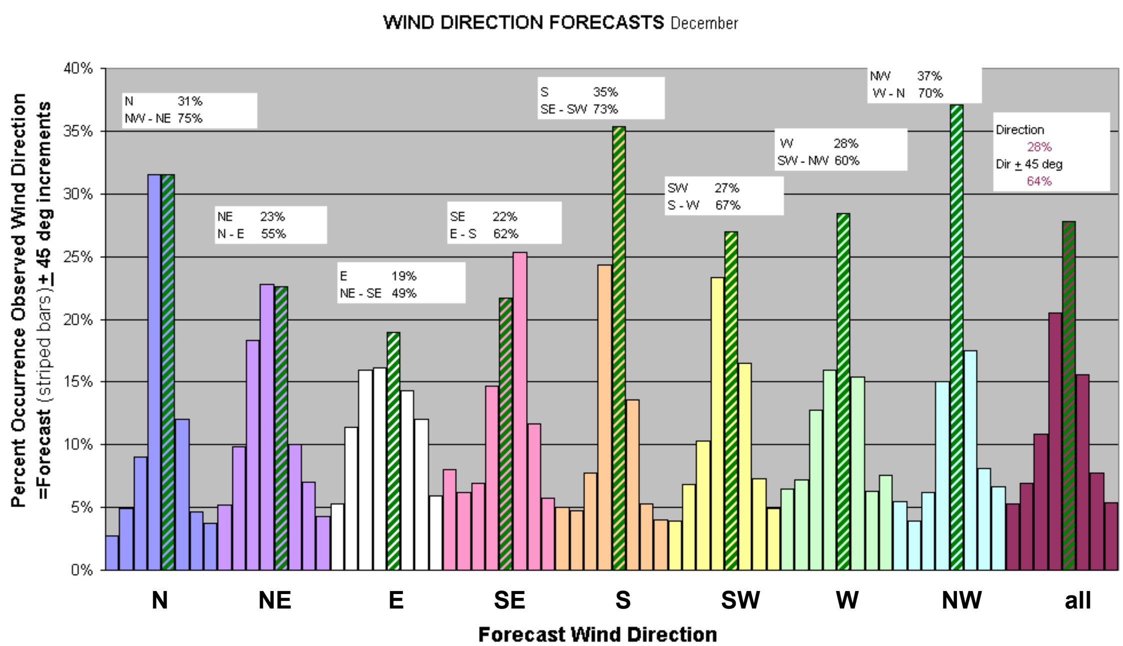

Figure 11. Bar Chart Version of Percentage of Wind Direction Forecast Error Categories by Forecast Wind Direction Value for December.

- For each forecast direction, the percentage of observations from that same direction is indicated by a striped bar.
- The bars to the immediate left of the striped bar for each specific color include the percent of cases where the observed wind was one 45º wind category counter-clockwise to the forecast category.
- Likewise, the bars to the immediate right of the striped bars include the total cases where the observed wind was one 45° wind category clockwise from the forecast category.
- The remaining bars to the left and right within each group show the percentage of time the observed wind direction is from categories increasingly distant from the forecast category in the counter-clockwise and clockwise directions, respectively.

The highest percentages of accurate forecasts occur when the forecast is for wind direction from the northwest, south, or north. When the forecast wind direction is north, the observed wind cases are very predominantly from the north or northwest. A similar statement can be made for northeast forecast winds, with the validating wind most often from the northeast or the adjacent counter-clockwise direction of north. However, northeast forecasts do not verify correctly as often as north wind forecasts, and forecasts for east winds show the lowest accuracy of any direction. This bar chart is included for illustrative purposes since it is only based on the eight forecast days in December. Another option for illustrating all the wind direction data is provided in table 3, which also includes only the December cases. Color coding can highlight trends for an initial inspection, but a thorough analysis of the results included in a table like this can still be time-consuming. The following list summarizes a few conclusions from the December wind direction forecasts.

- The forecasts with an easterly component were somewhat less accurate.
- Forecasts for south or northwest winds verified accurately most often, but south winds were still forecast more frequently than they occurred.
- Actual wind directions show up opposite from the direction forecast in about 5 percent of the cases, ranging from 3 percent when the forecast direction is north to 8 percent when the forecast direction is southeast. For this study, no information is provided on whether or not frontal passages occurred on the included dates, potentially leading to timing errors on wind direction shifts.
- The observed wind direction was within the correct or adjacent compass wind direction the majority of the time, ranging from 49 percent of the forecasts for east winds to at least 70 percent of the cases when the model forecast winds were from the northwest, south, or north.

Table 3. Percent of the Time the Wind was Actually Observed From Each Compass Direction for Each Forecast Direction.

FORECAST WIND DIRECTION \ OBSERVED WIND DIRECTION	N	NE	E	SE	S	SW	W	NW	Number of Fcsts from the Given Wind Direction	
N	0.31	0.12	0.05	0.04	0.03	0.05	0.09	0.31	667	6%
NE	0.23	0.23	0.10	0.07	0.04	0.05	0.10	0.18	601	6%
E	0.16	0.16	0.19	0.14	0.12	0.06	0.05	0.11	490	5%
SE	0.06	0.07	0.15	0.22	0.25	0.12	0.06	0.08	1264	12%
S	0.05	0.05	0.08	0.24	0.35	0.14	0.05	0.04	4073	38%
SW	0.05	0.04	0.07	0.10	0.23	0.27	0.16	0.07	1846	17%
W	0.06	0.08	0.07	0.07	0.13	0.16	0.28	0.15	1046	10%
NW	0.18	0.08	0.07	0.06	0.04	0.06	0.15	0.37	617	6%
Number of Obs from the Given Wind Direction	973	777	921	1703	2458	1504	1133	1165	10634	
	9%	7%	9%	16%	23%	14%	11%	11%		

< 10%

10-20%

20-30%

30-40%

For the given forecast wind direction, the cell color depicts the percent of time the observed wind is from the noted direction

Cells enclosed in double borders indicate the observed wind is from the same direction as the forecast wind

0.00 Red text indicates the observed wind is from the opposite direction as the forecast wind

Returning to the complete results for all three months, figure 12 depicts the relationship between the percent of accurate forecasts and the forecast value for temperature, dew-point temperature, wind speed, and wind direction.

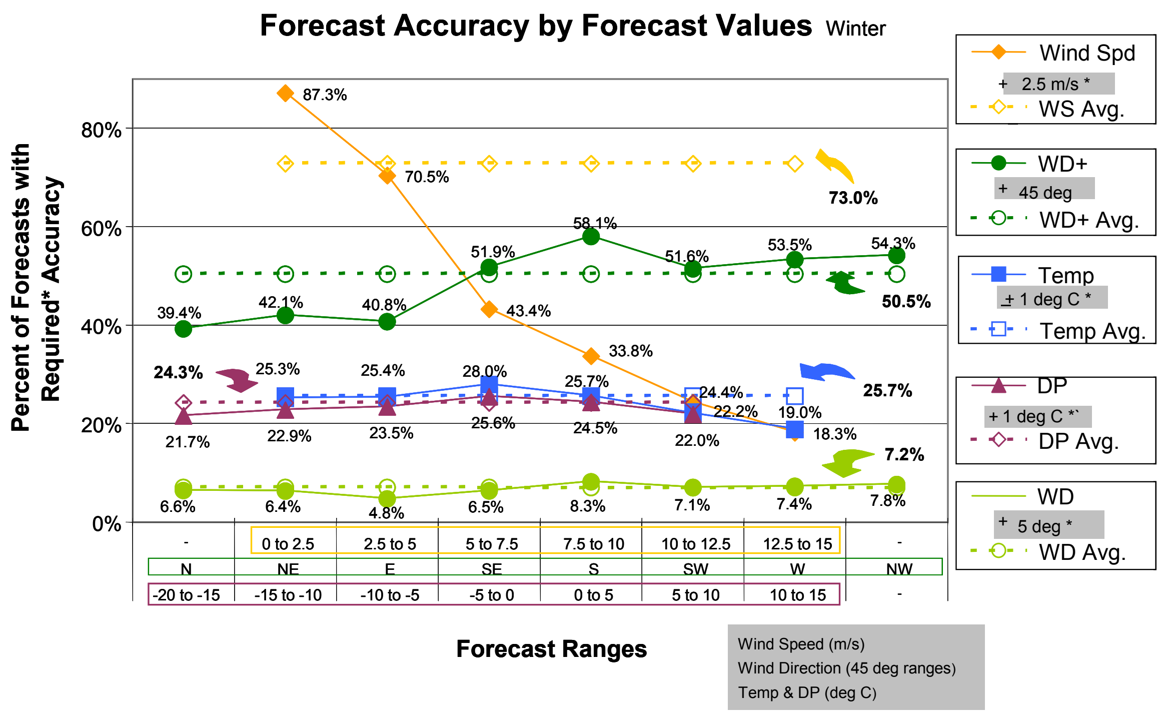

Figure 12. Percentage of Forecasts Satisfying Required Accuracy by Forecast Value.

As with the observed values, when the forecast value is for an infrequent occurrence, it tends to be less accurate.

- Obviously, the most notable trend is the steep drop in accuracy as wind speeds become higher.
- A lesser but still significant difference exists between wind forecasts for north to east winds being accurate about 10 percent less frequently than from other directions. These numbers are not equivalent to the ones presented in figure 11 or table 3 because those included only the December model runs. Also, the previous discussions were based on discrete compass direction categories, while figure 12 wind direction accuracy percentages rely on a straight calculation of the difference between observed wind direction and forecast wind direction being less than 45º.
- Only a slight impact can be seen on the hottest or coldest forecast temperatures and dew-point temperatures.

3.5 Forecast Errors Associated with the Station Elevation

Forecast models are frequently presumed to have difficulty handling complex terrain. The elevation may not be resolved well at specific station locations, and the scale of local orographic effects may not be represented by the model physics. The northern Utah area used in this study consists of widely varying terrain, so it seems logical to look for a correlation between station elevation and forecast accuracy. The surface stations were arbitrarily divided into categories of low (below 1500 m), middle (1500-2200 m), and high (above 2200 m).

The temperature errors for each of the three elevation categories are shown in figure 13. The forecast bias toward too warm temperatures is most prevalent at the higher stations.

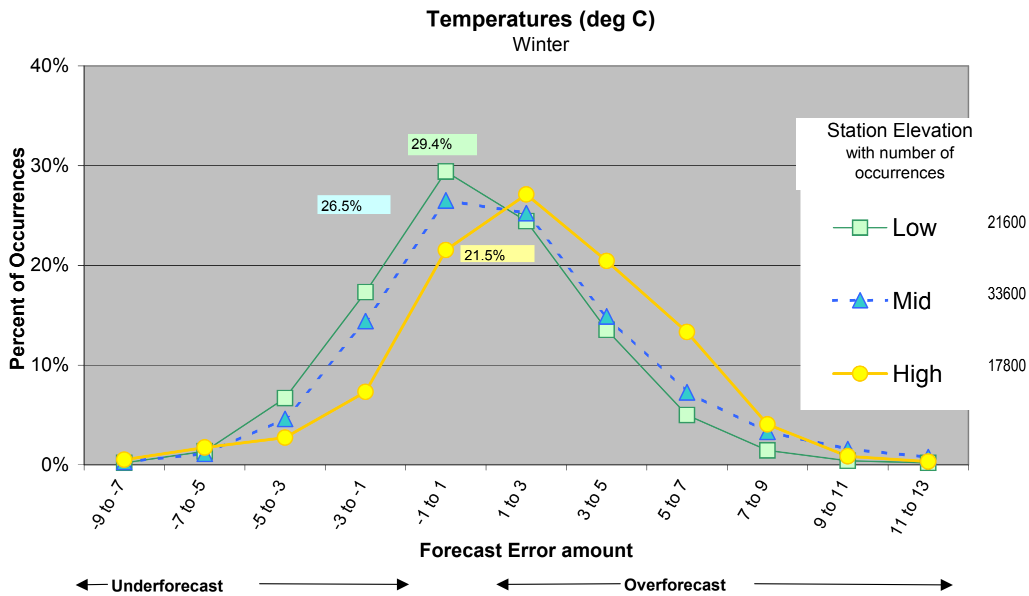

Figure 13. Percentage of Temperature Forecasts with Specified Error Amounts by Station Elevation.

The dew-point temperature accuracies are similar to those for the temperature forecasts, but the low stations show a greater improvement over the middle stations, as seen in figure 14.

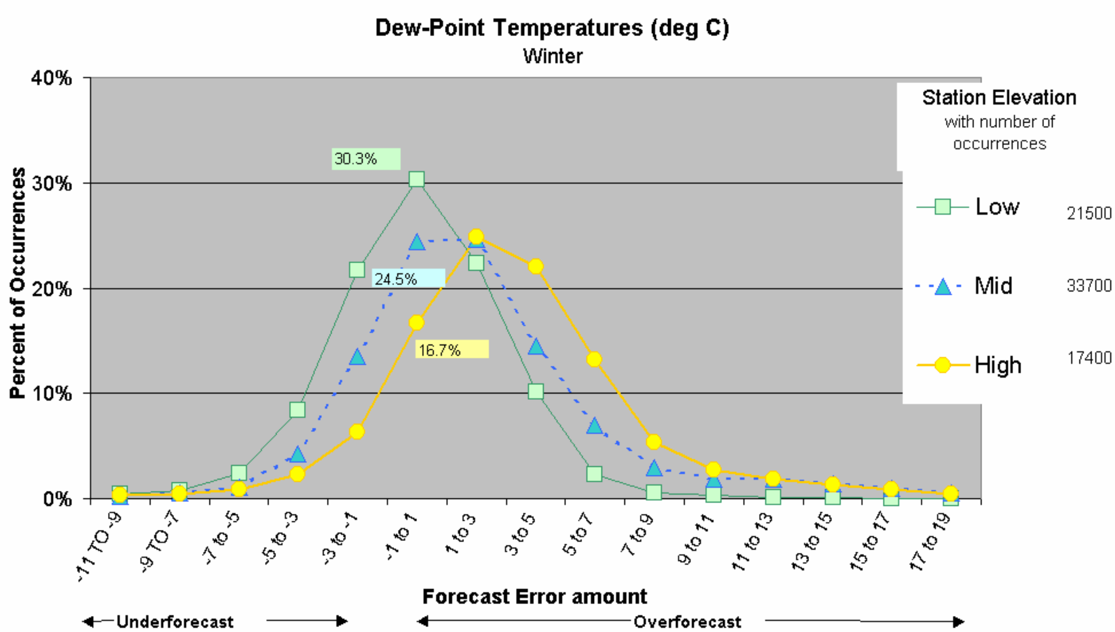

Figure 14. Percentage of Dew-Point Temperature Forecasts with Specified Error Amounts by Station Elevation.

Figure 15 portrays the wind speed forecast accuracy by station elevation. These appear only a little less accurate at the high stations.

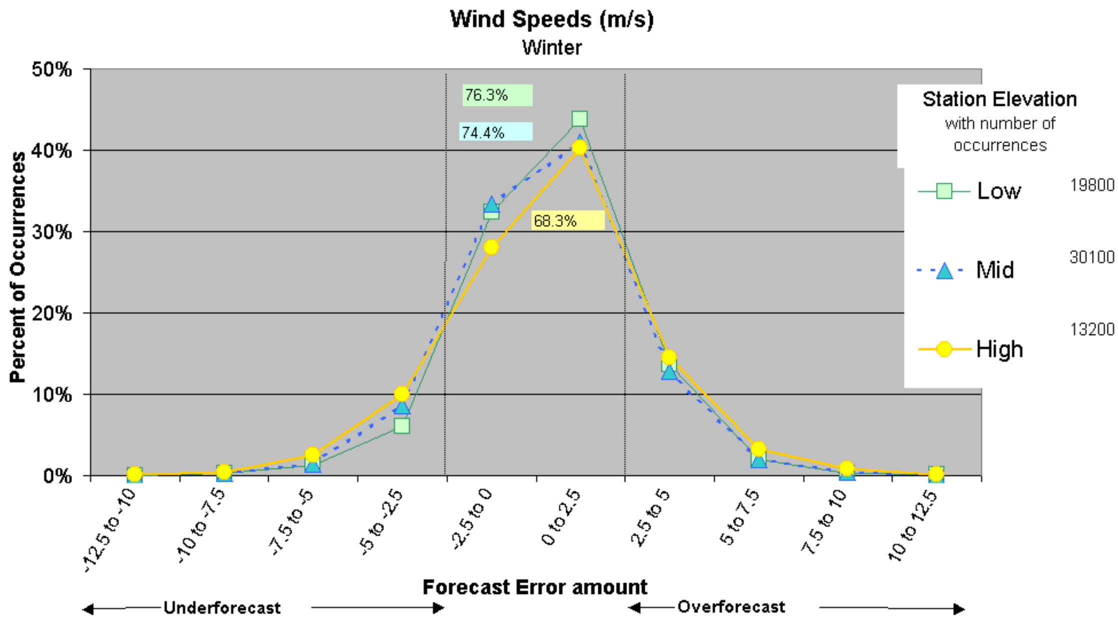

Figure 15. Percentage of Wind Speed Forecasts with Specified Error Amounts by Station Elevation.

On the other hand, figure 16 reveals wind direction forecasts significantly more accurate at the high stations. Cases with wind speeds below 1 m/s are omitted in these results, but it is still likely that greater wind direction variability at the lower stations causes more difficulty in forecasting this parameter.

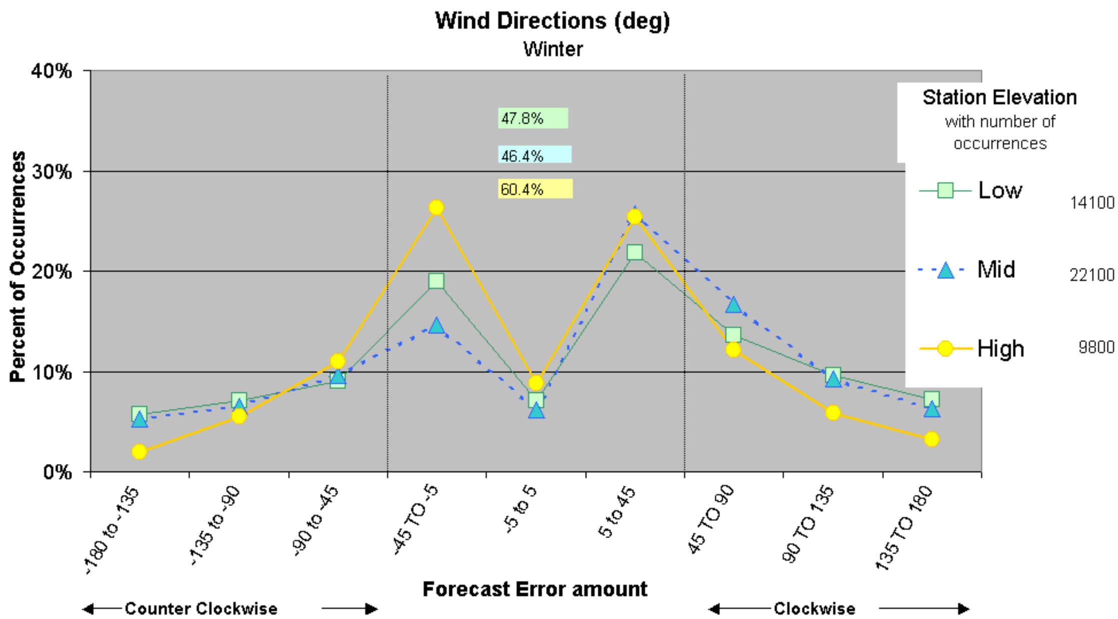

Figure 16. Percentage of Wind Direction Forecasts with Specified Error Amounts by Station Elevation.

This study indicated that varying forecast error amounts may be associated with station elevation, based on data from many surface stations in each of the selected elevation categories separated by 1500 and 2200 m (4900 and 7200 ft). A check of the lowest and highest subset of the stations below 1300 m and above 2500 m did not highlight any great differences from the less stringent definition used for low and high stations. The forecast error trends as a function of station height are summarized below:

- Temperatures and dew-point temperatures were more likely to be over-forecast at the high stations.
- Since the dew-point error tends to be in the same direction as the temperature error, relative humidity forecasts might not reflect as much difference between the higher and lower stations.
- Wind speeds were somewhat less accurate at the high stations, but not by a lot considering they can be expected to be stronger with more room for error.
- The wind direction forecasts were accurate more often at the high stations.

3.6 Forecast Errors for All Cases

In this study, it appears that consideration of the station elevation may provide some insight into the frequency of various errors in the MM5 forecasts. These differences cannot be generalized to other locations or times. Since the forecast errors don't appear to vary significantly with several of the factors considered, it seems worthwhile to view the total occurrence of the error amounts for all the cases together. However, it is still true that these findings cannot be assumed to represent MM5 errors for other times or places.

Figures 17 through 20 show the frequency of the various error amounts for temperature, dew-point temperature, wind speed, and wind direction, respectively, for all the forecasts and stations combined.

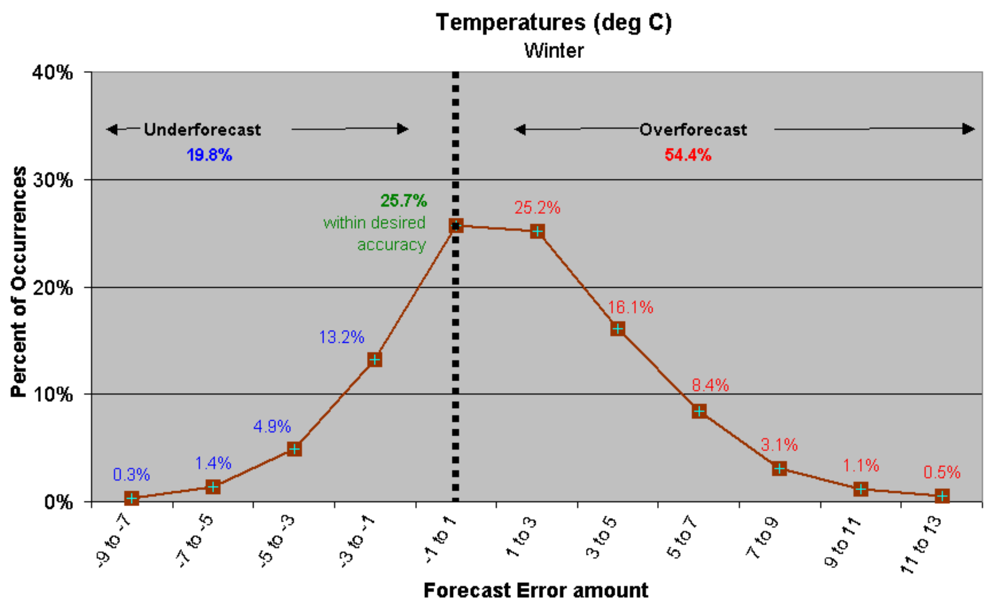

Figure 17. Percentage of Temperature Forecasts with Specified Error Amounts for all Stations and Forecast Times Combined.

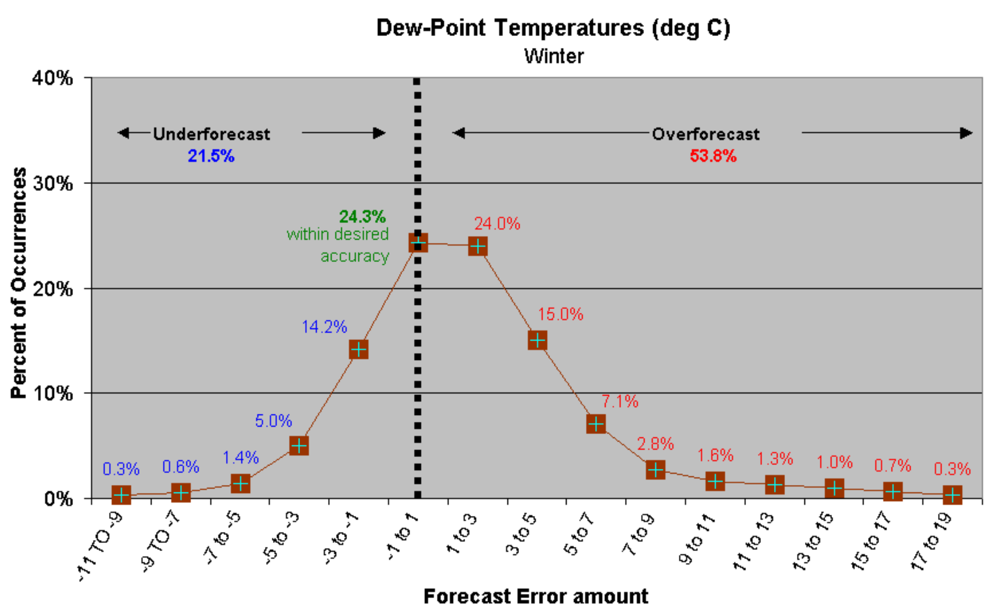

Figure 18. Percentage of Dew-Point Temperature Forecasts with Specified Error Amounts for all Stations and Forecast Times Combined.

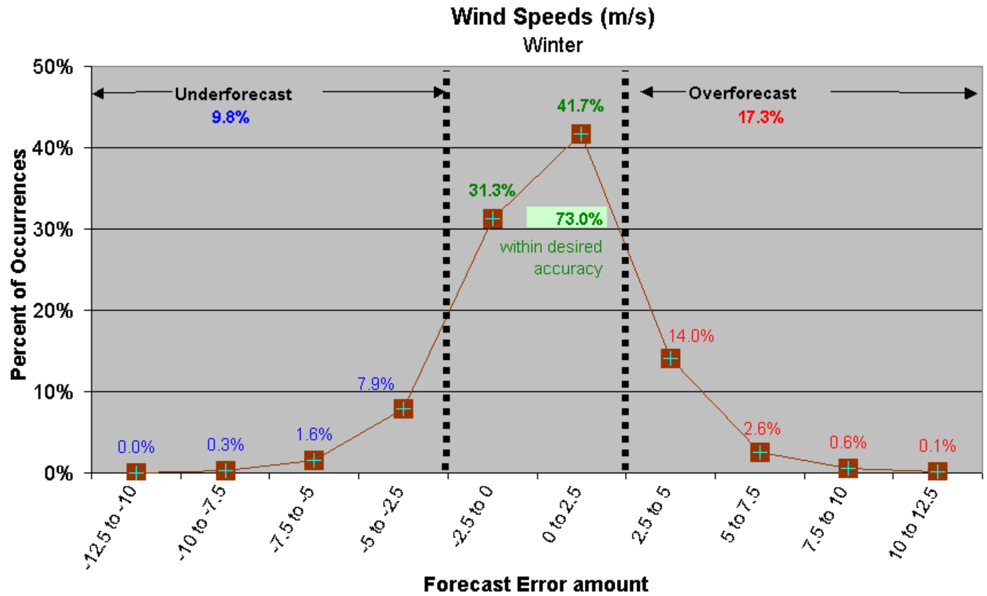

Figure 19. Percentage of Wind Speed Forecasts with Specified Error Amounts for all Stations and Forecast Times Combined.

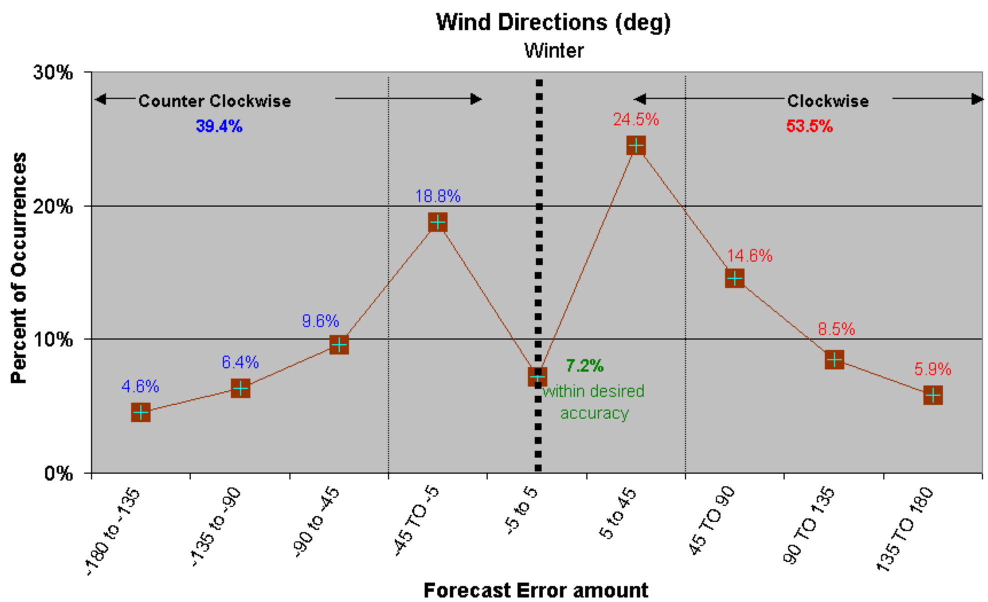

Figure 20. Percentage of Wind Direction Forecasts with Specified Error Amounts for all Stations and Forecast Times Combined.

4. Conclusions

4.1 Relating Error Amounts to User Forecast Uncertainty Calculations

The previous charts all take a fair amount of study to determine the probability of various forecast errors. Table 4 presents a simplified method for users to incorporate previously observed errors into forecast uncertainty calculations. A user would choose the confidence level desired for the weather forecast, based on its criticality. Then the single forecast value output by the MM5 model would be turned into a range of values by adding and subtracting the amount listed for the confidence level chosen and the parameter of interest.

Table 4. User-Selected Confidence Desired to Generate a Forecast Range Based on the Frequency of Forecast Errors.

CONFIDENCE LEVEL DESIRED		TEMP (°C)	DP TEMP (°C)	WND SPD (m/s)	WND DIR (degrees)
5%		0.2	0.2	0.1	3
10%		0.4	0.4	0.2	7
15%	***Determine***	0.6	0.6	0.4	11
20%	***a Forecast***	0.7	0.8	0.5	15
25%	***Range by***	0.9	1.0	0.6	19
30%		1.1	1.2	0.8	23
35%	***Using the***	1.4	1.5	0.9	28
40%	***MM5***	1.6	1.7	1.1	33
45%	***Forecast***	1.8	1.9	1.2	38
50%	***Value***	2.1	2.2	1.4	44
55%		2.3	2.4	1.6	51
60%	***plus***	2.6	2.7	1.8	59
65%	***and***	2.9	3.0	2.1	68
70%	***minus***	3.3	3.4	2.3	78
75%		3.7	3.9	2.6	91
80%	***the amount***	4.2	4.4	3.0	105
85%	***indicated***	4.9	5.1	3.4	121
90%		5.7	6.0	4.1	137
95%		7.0	8.2	5.0	154

Alternatively, an experienced staff weather officer (SWO) could determine a high, medium, or low confidence in the model run based on knowledge of the weather situation and the particular forecast involved. Table 5 shows values that could be used to modify the single forecast value in these cases. The ranges associated with these high, medium, and low confidence levels are similar to the user's desired 25 percent, 50 percent, and 75 percent confidence levels, respectively.

Table 5. Staff Weather Officer Confidence Assigned to Generate a Forecast Range Based on the Frequency of Forecast Errors.

CONFIDENCE LEVEL ASSIGNED BY SWO		TEMP (°C)	DP	WND SPD (m/s)	WND DIR (degrees)
HIGH	***Forecast Value***	1	1	0.5	20
MEDIUM	±	2	2	1.5	45
LOW	***Amount Indicated***	4	4	2.5	90

NOTE: Red cells include ranges greater than specified in Army requirements.

Bias trends have been ignored in the forecast ranges calculated from the values in tables 4 and 5. Correcting for biases, if known, would result in smaller forecast ranges for each confidence level. In the forecasts used for this study, the improvements based on correcting for bias errors would be most pronounced for temperature and dew-point temperature. Cells shaded red in table 5 highlight forecast ranges larger than the Army's stated accuracy requirement. Note that a model forecast at the high confidence level would still result in a total wind direction forecast range of 40°. If users truly find this amount of variability to be unacceptable, they certainly wouldn't be satisfied with the vast majority of wind direction forecasts.

4.2 Recommendations

This study approached weather forecast uncertainty as a function of historical model errors. Many thousands of MM5 forecast values were compared to observations. However, this "history" was limited in time to three months in a single winter season, and in space to a single geographic area around northern Utah. Even within this limited domain, it is difficult to clearly identify variables that can be associated with more or less forecast uncertainty. The most promising variable appeared to be station elevation. Many more cases would need to be examined over different times and locations to determine if the forecast errors seen in this study are representative of overall MM5 performance.

The statistics generated and presented in this and similar studies could be used to answer a general question of the typical accuracy of a forecast model. But decision makers on the battlefield would benefit much more by having information on the specific uncertainty associated with the individual day's forecast. Additional efforts to quantify model forecast error will be useful.

In addition to expanding the time and space coverage of model accuracy statistics, they may be used to determine and correct for model biases. Other efforts hold more promise for providing insight into the expected error on a particular day. A possible follow-on study to the one presented in this paper could find how closely errors from the previous day or two's model runs correlate to an individual day's forecast error from the same model. It seems logical to assume that when a forecast turns out to be wrong one day, users will have a lower confidence in its accuracy the next day.

Statistics on the length or repetitiveness of poorer-than-average model performance may be useful. Although model ensembles are not currently available on the battlefield, information from ensembles may someday be used to estimate weather forecast uncertainty in tactical situations. Methods to provide uncertainty information to decision makers will need to be automated and easy to interpret. Additional information only has value if it leads to better outcomes.

Both civilian and military agencies are pursuing efforts to facilitate better decision making in the face of weather forecast uncertainty. The U.S. Army Research Laboratory (ARL) is currently sponsoring Small Business Innovation Research contracts with this goal in mind. In addition, the Department of Defense (DoD) Center for Geosciences/Atmospheric Research at Colorado State University will continue to coordinate with ARL to address Army needs in atmospheric research, including the use of model ensembles.

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Acronyms

ARL	U.S. Army Research Laboratory
CISD	Computational and Information Sciences Directorate
DoD	Department of Defense
IWEDA	Integrated Weather Effects Decision Aid
MM5	Penn State/National Center for Atmospheric Research fifth-generation Mesoscale Model

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